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Critical Errors in Infrequently Performed Trauma Procedures after Training.

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Brief Title: Critical Errors in Infrequently Performed Trauma Procedures

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Abstract:

Background: Critical errors increase post-operative morbidity and mortality. A trauma readiness index (TRI) was used to evaluate critical errors in four trauma procedures performed by general surgery residents, practicing surgeons, and expert traumatologists. Trained evaluators used a standardized script to evaluate performance on unpreserved cadavers[deleted text]. In comparison to practicing and expert surgeon benchmarks, we hypothesized that TRI would increase and errors decrease in residents after training.

Study Design: Prospective study

Results: Forty residents were evaluated before, immediately after Advanced Surgical Skills for Exposure in Trauma (ASSET) training, and 38 were re-evaluated14 months later. Residents were compared to 34 practicing surgeons evaluated once 30 months following training, and 10 expert traumatologists. Frequency of critical errors performed by residents decreased immediately following ASSET training ($p<0.01$), fourteen months later was no different to experts, but less than made by practicing surgeon ($p<0.0001$). [removed text] Experts had 5-7 times better error recovery than practicing surgeons or residents. Resident TRI increase with training ($p<0.001$), remained unchanged 14 month later and was higher, with lower variance than practicing surgeons ($p<0.05$). Expert TRI was higher than residents ($p<0.004$) and practicing surgeons ($p < 0.001$). TRI below the 5th decile predicted critical errors in all cohorts.

Conclusion: Resident training decreased critical errors when evaluated immediately and 14 months after ASSET training. Practicing surgeons had more critical errors and performance variability than residents or experts. Low TRI was associated with critical errors occurring in all surgeon cohorts and can identify surgeons in need of remedial intervention.

Background

Medical errors are a focus topic of patient safety and have recently been reported as the third leading cause of death in the U.S[1]. Surgical errors in particular can have severe consequences, including preventable deaths[2]. In the 1991 Harvard Medical Practice study[3], 53% of adverse events were associated with an operation. Of these 26% were operative technical adverse events and 10% were due to failure to achieve surgical goals; among 697 performance errors, technical errors accounted for 76%. Similarly, 28 hospitals in Colorado and Utah reported nine years later that operative adverse events were about half of the adverse events, and most operative adverse events were attributed to surgeons (46%), with 22% identified as negligent and 17% resulting in permanent disability[4]. Efforts in surgery to reduce errors include the World Health Organization safety checklist[5], The Joint Commission National Patient Safety Goals[6],[7] and initiatives to address disclosure and management of surgical errors[8]. However, few studies have focused on errors among individual surgeons.

Trauma surgery is a core skill for general surgeons. Trauma surgical competency is required for residents by the American Board of Surgery, including experience in surgical critical care, trauma/burns and emergency surgery, and vascular surgery[9]. General surgeons in rural practice especially need be competent to provide the first level of surgical stabilization for trauma patients, as this may be necessary, on an infrequent basis[10]. Additionally, the military faces ongoing challenges in maintaining a ready corps of general surgeons for deployment[11].

In this study, we sought to determine the long-term impact of a one-day cadaver-based training course on critical errors occurring during performance of trauma-related surgical procedures. In comparison to practicing and expert surgeon benchmarks, we hypothesized that Trauma Readiness Index TRI would increase and errors decrease in residents after training.

Methods

The study was conducted at the Maryland State Anatomy Board cadaver laboratories situated at the University of Maryland School of Medicine (UMSOM). UMSOM Institutional Review Board and US Army Medical Research and Material Command Office of Research Protection approved the recruitment and consent process. Cadaver use was approved by the Maryland State Anatomy Board and US Army. Enrolled surgeons received training in the Advanced Surgical Skills for Exposure in Trauma (ASSET) course, a 1-day human cadaver-based skills course that systematically reviews all of the major vascular exposures in the body [12]. For the study, after informed consent was obtained, participants were presented with four case-based scenarios involving representative ASSET procedures (4 of 59 procedures taught during the course).

Using a standardized script, study participants responded to questions relating to initial trauma resuscitation, diagnosis, management, and anatomy, and were asked, without any feedback or instruction, to perform four procedures related to the cases: vascular exposure with proximal control of the axillary (AA), brachial (BA) and femoral (FA) artery (including individual control of common, superficial and profunda femoral arteries) and LE fasciotomy with four compartment decompression (FAS) in fresh cadavers. Performance was evaluated by 2 co-located, trained evaluators. Following the completion of all 4 procedures, the evaluators debriefed the surgeons regarding their performance [13-16]. Residents from 13 different Mid-Atlantic surgical training programs. were recruited by mailing letters to the Program Directors. Practicing surgeons from twenty-five different North American regions, who had received ASSET training between 2-4 years prior, were recruited by e-mail from American College of Surgeons listings of ASSET participants, as previously described, these surgeons had a broad-spectrum of sub-specialization [16]. [revision: Deleted Section here]

Critical technical errors (e.g., failure to loop the artery proximal to injury within 20 minutes) and critical management errors (e.g., delay in going to the operating room) that were potentially life-threatening were recorded for each procedure (Table 1). All participants were evaluated using an Individual Procedure Score (IPS) [13-16] and the sum of the IPS for each of the 4 procedures was calculated as the Trauma Readiness Index (TRI)[15]. These metrics divided overall surgical technical and non-technical skill into 5 components: trauma patient knowledge, anatomy (landmarks, incision and structures), patient management, procedural steps, and technical skill.[13-16] Errors in technical skills, and management errors (Table 1) were evaluated for each procedure. IPS was the sum of the correct component scores / total possible score. Scoring, errors and time to complete each procedure were noted. Critical technical and management errors and their contribution to each procedure IPS (subtraction of 2 points per critical error) and error recovery (subtraction of only 1 point for self-recognition and correction of the error) were defined by a panel of expert trauma surgeons in a series of consensus conferences [14,15]. Errors per surgeon and error recovery per surgeon among residents tested at intervals before, immediately after, and 12- 18 months following the ASSET course were compared to errors and error recovery per surgeon among the practicing and expert surgeon cohorts. As previously described, performance data were entered into a touch-screen mobile Android ® Tablet application (App) in real-time, and all procedures were video-recorded [13-16]. Total time to complete each procedure was recorded by the App. [revision Deleted Section here]The experience levels for each surgeon cohort were categorized as high, medium and low (by tertiles of the enrolled cohort experience) for each procedure.

Statistical Analyses: Linear mixed modeling was used for TRI comparisons among residents, practicing, and expert surgeons and general linear modeling for identifying the effects of months and interval experience on making critical errors. The models included the following differences between the surgeon cohorts: time since ASSET training, interval experience (numbers of trauma patient evaluations, numbers of UE and LE procedures), cadaver body habitus (obese, average or thin) and relationship to components of IPS including: knowledge, anatomy, patient management procedural steps, technical skills. Tukey-Kramer adjusted p-values were used for multiple IPS and TRI comparisons with critical errors as the primary outcome. The average of the squared differences from the mean TRI values among the surgeon cohorts, was used to measure individual surgeon variance of TRI at each evaluation. Modeling included identification of features of the TRI that gave the highest sensitivity and specificity for prediction of critical technical error occurrence, defined by the Area Under Receiver Operating Curve. Statistical Analysis Systems (SAS) v 9.3 (Cary, NC) was used for analyses with $p < 0.05$ considered significant. *A priori* sample size calculation required 36 of 40 (90%)

originally enrolled residents to be followed-up for re-evaluation to detect changes in skill, including errors, of 0.70 SD and 0.82 SD with 80% and 90% power, respectively using a two-tailed t-test with 5% type I error.

Results

Eighty-four surgeons participated in the study, but two surgeons did not complete follow-up skill retention evaluations [13-14]. Enrolled participants included 40 post-graduate year 3-6 general surgery residents evaluated before they received ASSET training with follow-up within 1 month and 38 of 40 residents returned again 14±2.7 (mean± standard deviation [SD]) months after ASSET training for skill retention evaluation. Other participants included 34 practicing surgeons evaluated 30 ±12.8 months after ASSET training, and 10 experts 46±6.3 months since ASSET training. Their interval experience between ASSET training and participation in the study showed large variability[16] with some surgeons, including experts, in each cohort having performed none of these upper or lower extremity vascular procedures or FAS since training, while all except the lower tertile of practicing surgeons had evaluated some trauma patients.

<u>Resident Pre-Training Critical Errors versus Practicing and Expert surgeons</u>

The number of critical errors (critical technical errors + critical management errors) by the residents pre-ASSET training were higher ($p < 0.0001$) than all the same resident post-training evaluations, and higher than practicing surgeons ($p<0.05$) and experts ($P<0.0001$). There were a mean 3.4 critical errors per resident surgeon before training, and 3.0 per resident after training ($p < 0.01$) versus 1.6 per resident at mean 14 months post-training retention evaluations among 38 of 40 of the same surgeons ($p < 0.0001$). Pre-training critical errors were greater ($p < 0.05$) in residents, compared to 2.8 critical errors per practicing surgeon. Significantly ($p < 0.0001$) fewer critical errors were made by experts (1.4 errors per expert) than residents evaluated immediately after training. After 14 months there was no difference between residents and experts in critical errors while practicing surgeons had significantly greater number of critical errors($p < 0.0001$) (see Fig 1 and Table 2).

Critical Technical, Management Errors and Error Recovery among the 3 cohorts of surgeons

The frequency of critical technical and management errors and frequency of error recovery for all surgeons is shown in Table 2. Critical technical errors decreased from 112 (mean 2.8/surgeon) to 46 (mean 1.2/surgeon) in the 40 residents and remained unchanged when skill retention was revaluated. Practicing surgeons had mean 1.6 critical technical errors/surgeon and experts mean 1 critical technical error /surgeon. Critical management errors included inappropriate use of angiograms or other pre-operative investigations that would delay surgical control of bleeding in the operating room. Practicing surgeons had 10 times the critical management errors compared to residents at their skill retention evaluation 12- 18 months after training. One expert made a critical management error. Error recovery per surgeon identifies the ability to recognize and self-correct errors[17], error recovery per unit critical error per surgeon (to account for the differing numbers of potential errors, multiple procedures and surgeons in each cohort) for experts (2.1) was about seven times that of pre-trained residents (0.26) and practicing surgeons (0.33) and about five times that of residents after training (0.38) and at their 14 month evaluation (0.43) (Table 2). Because the error recovery rate was low in all cohorts, none of these differences were statistically different.

Multiple Critical Technical Errors

Among 40 residents, no resident performed the four procedures before ASSET training without making a critical technical error, 5 residents made one critical technical error, 9 made two, 15 made three, and 11 made four. Immediately after training, 11 residents (27.5%) made no critical technical error, 18 residents made one critical technical error, 6 made two, 4 made three, and 1, one four critical technical errors. In 38/40 residents who returned for skill retention evaluation at a mean 14 months after ASSET training, 8 made no critical technical error (21%), 16 made one critical technical error, 11 made two, and 3 made three. Among 34 practicing surgeons evaluated once, mean 30 months after ASSET training, 11 made no critical technical error (32%), 11 made one critical technical error, 11 made two, none made three, and one made 4. Among the 10 experts, two made no critical technical errors (20%), six made one critical technical error and two made two. Four residents made the same errors before and after training, including failure to identify a specific artery or failure to decompress a specific compartment of the leg. For the vascular procedures, 10 residents failed to expose the same one or more arteries at each of the three evaluations. For the fasciotomy procedure, 38 residents completed the evaluation at three separate intervals, the same 5 residents did not decompress the anterior compartment on any of the three evaluations, 4 did not decompress the lateral compartment, 5 did not decompress the superficial posterior compartment, and 16 did not decompress the deep posterior compartment. One resident surgeon did not decompress any of the four compartments on any of the three evaluations, and 6 surgeons failed to decompress more than one compartment each time.

Trauma Readiness Index (TRI) among Residents, Practicing Surgeons, and Expert Surgeons

TRI was significantly higher, with lower variance (TRI 0.8, SD 0.04) for experts compared to residents pre-training (TRI 0.53, SD 0.07), < 1 month post-training (TRI 0.67, SD 0.07) and 12-18 months (mean 14 months) post training (TRI 0.67, SD 0.07). Practicing surgeons (TRI 0.66, SD 0.08) had lower TRI ($p < 0.05$) and higher variance than experts and residents after training (Figure 2).

When all participant surgeons were stratified into performance deciles based on overall TRI scores, the frequency of errors versus the performance decile showed that 98% of surgeons in the lowest decile made a critical technical error (Figure 3) and errors increased < 5^{th} TRI decile. Performance and errors are linked. The TRI at the 5th decile of the resident cohort was pre-training median 0.53, 95% confidence interval (CI) 0.5, 0.56, at 12-18 month resident follow-up median 0.67, CI 0.65, 0.69. For practicing surgeons TRI at the 5^{th} decile was 0.66, CI 0.63, 0.68; and for experts 0.77, CI 0.72, 0.8. The 5^{th} decile of TRI (median 0.66-0.67) potentially identified a target group of resident and practicing surgeons who would benefit from additional training interventions.

Prediction of errors among residents using Area Under Receiver Operating Curves (AUROC) for TRI

Using features of the TRI including: all knowledge score, critical management, and error recovery to predict any future error with pre-training TRI of residents gave an AUROC of 0.98 indicating a high specificity and sensitivity for prediction of making a critical error in future performance of these four ASSET procedures.

Discussion

Making errors is part of normal human behavior[18]. Surgical competency involves a combination of good decision-making (pre-operatively, operatively and post-operatively), team performance and communication (with surgical, anesthetic, nursing and other essential staff members) and technical skill. These skills, coupled with a high patient and operative volume, tend to achieve a reduced patient mortality and morbidity[19,20]. It is unlikely that no errors occur throughout this process, even for the simplest of cases [20]. Using an overall TRI skill evaluation of vascular and non-vascular open surgical procedures benchmarked by practicing surgeons and expert trauma surgeons, this study demonstrated that an intensive 1-day trauma exposure training course was associated with a reduction in errors among the resident cohort evaluated 14 months after training, no different to error occurrence found among experts. Total errors, including specific critical technical and management errors and repeated errors representing life- and limb-threatening failures, were higher among practicing surgeons who took the ASSET course an average of 2.5 years prior to the evaluations, with a majority of the practicing surgeons having limited interval exposure to the four trauma exposures[16]. For critical technical errors there really was little difference between the groups in that the majority of all cohorts made technical errors. Only 21% of residents (evaluated at 14 months), 32% of practicing surgeons and 20% of experts completed all four procedures without making a single technical error. The critical technical error rate for fasciotomy, representing incomplete decompression of at least one compartment, was high among all three surgeon cohorts evaluated.

We have noted that individual surgeon errors could not be predicted based on time since training among residents[16]. We also found that there was large TRI (Fig 2) and error (Table 3) variability among the three surgeon cohorts, with the least variability seen in experts and most in practicing surgeons. As we have previously reported, practicing surgeons[16] had lower IPS than residents [13] and lower tertiles of performance judged by scatter plots of anatomy versus technical skills for vascular procedures, in which the highest tertile were no different than experts and the lowest tertile were identified as those in need of remedial intervention[14,16]. This study extends the findings to show when performance for multiple vascular and non-vascular procedures is summed (using TRI), similar variability in making errors is noted among all surgeons evaluated. Practicing surgeons evaluated as being in the uppermost performance tertile judged by the Trauma Readiness Index (TRI), performed a greater number of error-free procedures (32%) than experts or residents. This finding suggests that errors were more frequent in the lower tertile of practicing surgeons. Many residents made multiple and repeated errors, some on the same procedures. Although we recommend remedial intervention for these residents, we do not currently have evidence further training will improve performance for those who score poorly after initial training. This study also suggests, because performance and errors are linked, that TRI < 5th decile would be a useful metric for assessment of trauma-relevant procedures. Those residents performing below the 5th decile of TRI on the initial pre-training evaluation continued to make errors, including critical technical errors, and the same errors on the same procedures during repeat evaluations. Conversely, residents performing at the highest TRI level maintained a low error rate throughout the re-evaluation period. Most residents showed an overall improvement in TRI after the training intervention. Experts had about seven times better error recovery by recognizing their critical technical and management errors than practicing surgeons or residents before training. At resident skill retention evaluation, experts still had about five times the skill for error recovery after critical technical and management errors. This improvement in error recovery with training and the high error recovery seen in experts confirms the utility of error recovery as a performance metric for surgery[17].

Critical errors were observed in all of the study groups including experts. Indeed, only 2 of 10 experts performed all 4 procedures error-free, with the highest error rate in FAS where 6 of 10 made errors. This is in stark contrast to estimated overall error rates in medical practice, where a study examined 35,416,020 hospitalizations with 251,454 deaths stemmed from a medical error, a rate of ~0.7%[21] , although data was not presented on the breakdown of surgical versus other types of medical error. This study involved a surgeon operating without assistance when performing the procedure. It is reasonable to conjecture that a surgeon colleague in an assistant role serves an important error prevention or error recovery role in regular practice. This has important implications for military trauma, in which a high intensity engagement could overwhelm local surgeon availability necessitating surgeons operating 'solo' or with limited support at such times.

Detection of surgical technical errors in a skill laboratory has been previously identified as a surrogate for a more detailed skill assessment by direct observation during operative procedures, potentially allowing a less time-consuming method of skill assessment[17]. In our study, all surgeons operated without prompting or performance feedback, and some residents continued to make the same errors before and after training. The finding that an individual surgeon has a low TRI score does not require multiple evaluations to indicate that there is a likelihood the surgeon will make a critical error in performance of one or more of these procedures in the future. As a means of identifying surgeons in need of remediation interventions, at all levels of training, our findings indicate these surgeons could be identified at a single evaluation by an overall performance score below the 5th decile of TRI as scores below the 5th decile predict the occurrence of critical errors. Features of the TRI component scores can be used during pre-training evaluations to predict those individual surgeons who need intervention to prevent critical errors when operating independently. In the future, individual skill training, a term we have referred to as “precision training,” should allow individuals to identify their training needs and focus training accordingly[13]. This would be a departure from currently available training designed with a “one size fits all” model.

Medical error has been identified as a target for improvement, and understanding the factors contributing to errors is a key component to prevention of errors. Most serious medical errors occur in the high-risk areas, including the operating room, emergency department, and intensive care unit; error rates are higher among junior doctors.[8]. Among 133 study cases obtained from closed claims surgical malpractice analysis, 140 discrete technical errors were found with attending surgeons responsible for 69% and another 27% involving attending surgeons and trainees. Outcomes were death in 16% and permanent disability in 49% (68/140)[22]. All involved routine procedures with patients who had co-morbidities, complex anatomy, or repeat surgeries, or with equipment problems. We have shown that residents can be trained to similar performance and error rates as experts to perform open surgical vascular exposure and control and FAS under time-pressure by ASSET training. Previously we showed that correct landmark identification, skin incision placement and procedural steps increased IPS for each procedure and shortened time to completion[13-16].

Similar to our findings, a group of orthopedic interns who received an intensive surgical skills course were found to perform at a level close to senior residents, with the same level of performance persisting for at least 6 months [23]. Other authors have recognized the value of developing trainees as individuals, supporting training for decision-making, team performance, and surgical technical skill in a controlled environment with a goal of reducing errors in practice[20]. In addition, error management strategies may be an important component of performance improvement in surgical training, to include error recognition and recovery [24], as well as decision-making skills[25]. In our study, the primary type of error recovery observed was related to initial misidentification of anatomic structures, followed by realization of the mistake and correct identification. Therefore, increased familiarity with the specific surgical anatomy would be expected to result in more frequent and quicker error recovery. The lowest error recovery rate was observed in practicing surgeons a mean of 2.5 years after ASSET training, while the highest rate was observed in expert surgeons. In all groups, however, the majority of errors were not recognized or corrected.

The ability to recognize and treat compartment syndrome, including lower extremity fasciotomy, has been recognized as a core skill for trauma surgeons[26]. Military surgeons, in particular, may be called on to perform fasciotomy in austere settings without subspecialty support. Poorly performed fasciotomy is a source of significant morbidity, with revision for incomplete fasciotomy required in 17% of military casualties in one study[27]. In current civilian trauma practice, fasciotomy may frequently be performed by orthopedic consultants rather than trauma surgeons, potentially explaining the high rate of critical technical errors for fasciotomy even among expert trauma surgeons in our study.

Limitations

There may have been bias in the TRI scores because evaluators unavoidably knew who the experts were and when resident evaluations occurred in relation to pre-, post- and skill retention assessments after training. We rotated the resident evaluators so that wherever possible they did not evaluate the same residents. Like the residents and practicing surgeons, the experts were equally unaware about what skills would be evaluated in this study. The evaluations scripts and metrics were identical for all surgeons. Because of the possibility of learning bias among the residents evaluated three times performing the same four procedures within 12-18 months, we added a "surprise" additional procedure, carotid artery exposure, during the retention evaluation. As previously reported[16] no differences were found in IPS between this new procedure and the other 4 included in this study. However, fewer critical errors per resident surgeon seen 12-18 months after training, compared to evaluations immediately after training, may have resulted from repeated debriefings or due to the follow-up loss of two surgeons who had both made repeated errors at the pre- and post-training evaluations[13] .

An additional limitation in this study is that the practicing surgeons evaluated in this study were not evaluated at baseline, so it is impossible to know if their performance at a mean of 30 months was an improvement or a decrement from pre-training performance. Additionally, it is difficult to draw any conclusions as to the differences in performance between the residents and the practicing surgeons as the interval from initial ASSET course training was more than twice as long (30 months vs 14) and practicing surgeons interval experience was more varied[16].

Conclusions

Critical errors among residents decreased significantly after ASSET training. Critical errors were observed in all of the study groups including experts. Missed FAS compartment decompression is common among resident, practicing, and expert surgeons. A single evaluation using TRI can predict that an individual surgeon will make a critical technical or management error that will be limb or life-threatening, when performing the emergency vascular exposure and control or fasciotomy trauma procedures evaluated in this study. Individual skill training and repeated training is needed for all surgeons who rarely perform these trauma procedures. TRI is a tool to screen and focus such training accordingly to allow individual surgeons to identify their training needs. This would be a departure from currently available training designed with a “one size fits all” model

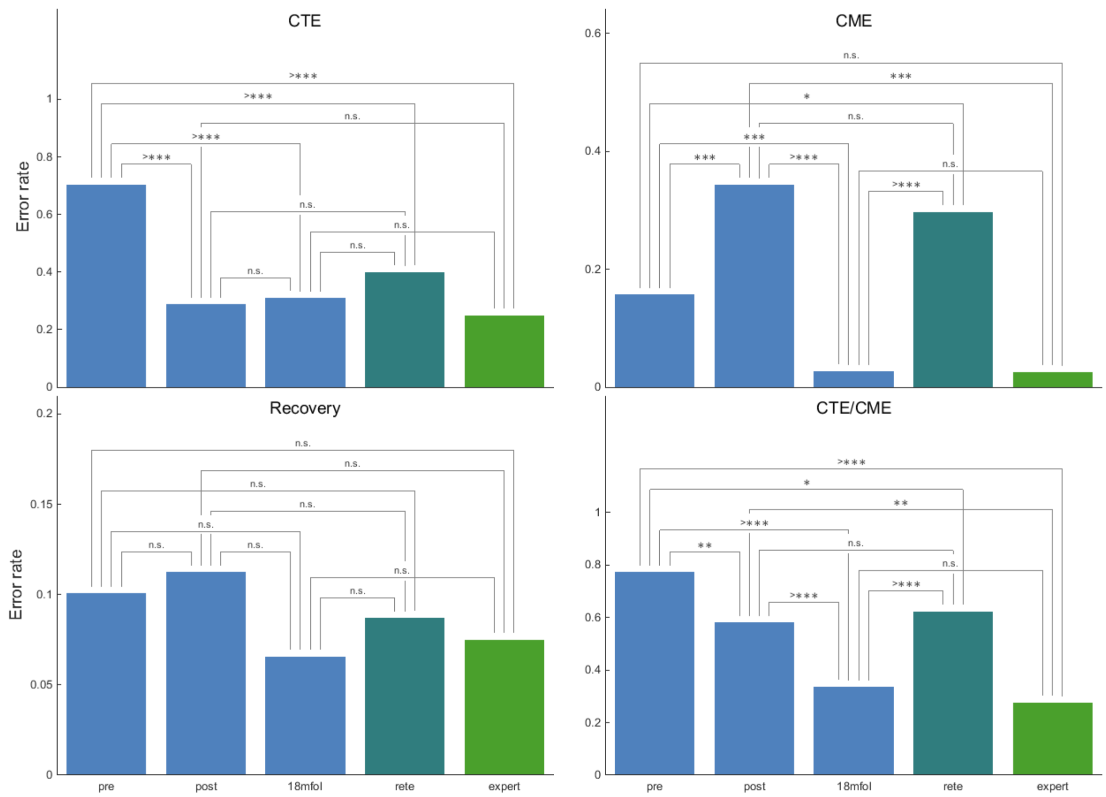

Figure 1: *Panel top left*: Differences between cohorts in Critical Technical Errors (CTE) rates; *Panel top right*: Critical Management Errors (CME); *Panel bottom left*: Error Recovery; *Panel bottom right*: Total Critical Technical and Management Errors. Figure shows differences between cohorts of residents, pre- post and up to 18 months after training; errors among Practicing surgeons (ret) and expert cohorts. *** = p <0.0001; ** = p = 0.0001-0.001; * = p 0.01-0.05; N.S.= no significant difference between cohorts in critical errors, although experts had five times the error recovery.

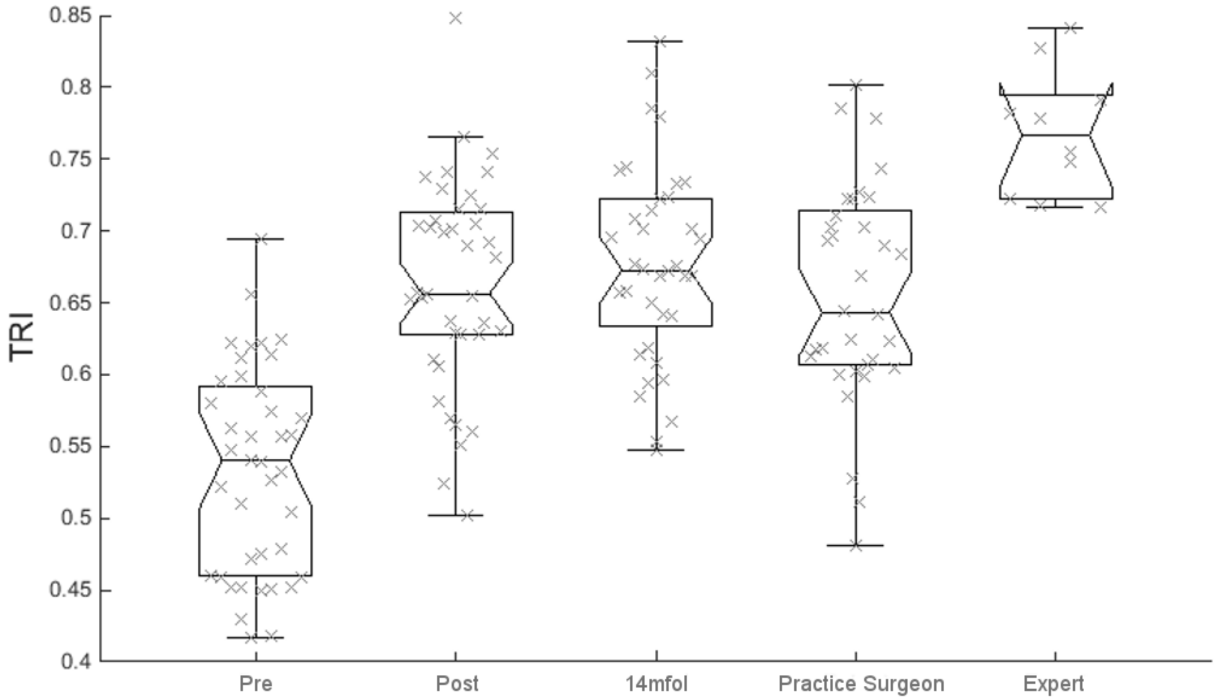

Figure 2. Mean +/- standard deviation, confidence intervals and individual surgeons Trauma Readiness Index (TRI) among all participant cohorts, Residents data = Pre-, Post and 14m follow up (see text for absolute values of TRI and differences between cohorts).

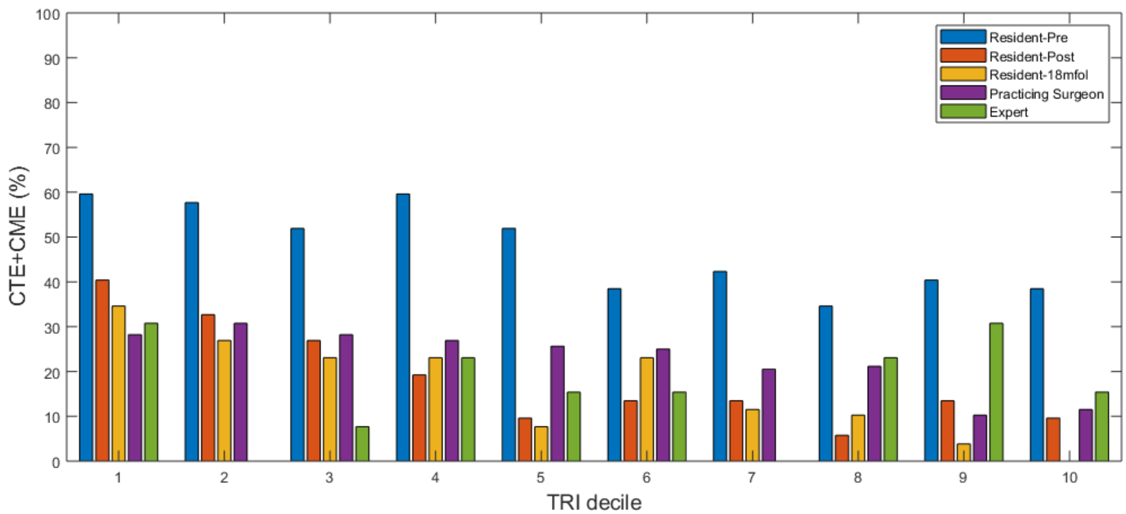

Figure 3: Deciles of Trauma Readiness Index scores for 3 vascular and one non-vascular procedure performed by 84 surgeons, including general surgery residents (evaluated pre-, post training and 12-18 months after training), practicing surgeons (evaluated once, mean 30 months after training) and expert surgeons (evaluated mean 40 months after training). The trend is for percent (%) Critical Technical Errors (CTE) + Critical Management Errors (CME) to increase below the 5th TRI deciles. 98% of surgeons in the lowest decile made a critical technical error. The 5th decile TRI score cut-off was 0.66 and 0.67 for residents evaluated 12-18 months after training and practicing surgeons, respectively

Axillary Artery	**Brachial Artery**	**Femoral Artery**	**Lower Extremity Fasciotomy**
CME: Inappropriate use of CT or Angiogram	CME: Inappropriate use of CT or Angiogram	CME: Inappropriate use of CT or Angiogram	CTE: Incorrectly identifies the intermuscular septum, does not recognize or correct error
CME: Delay in going to the operating room	CME: Delay in going to the operating room	Delay in going to the operating room	CTE: Fails to decompress Anterior Compartment, does not recognize or correct error
CME: Fails to obtain Chest Xray			CTE: Fails to open any of 4 compartments along entire length, does not recognize or correct error
CTE: Incorrectly identifies or fails to identify the Axillary Artery, does not recognize or correct error	CTE: Incorrectly identifies or fails to identify the Brachial Artery, does not recognize or correct error	CTE: Incorrectly identifies or fails to identify the CFA, does not recognize or correct error	ER: Incorrectly identifies the intermuscular septum, but is able to recognize and correct
CTE: Failure to loop the artery proximal to injury within 20 minutes	CTE: Failure to loop the artery proximal to injury within 20 minutes	CTE: Incorrectly identifies the SFA, and does not recognize or correct error	ER: Incorrectly identifies the Anterior Compartment but is able to recognize and correct
ER: Incorrectly identifies the Axillary Artery but is able to recognize and correct	ER: Incorrectly identifies the Brachial Artery but is able to recognize and correct	CTE: Incorrectly identifies the PFA and does not recognize or correct error	ER: Incorrectly identifies the deep posterior compartment but is able to recognize and correct
		CTE: Failure to loop artery proximal to injury within 20 minutes	ER: Incorrectly identifies the lateral compartment, but is able to recognize and correct
		ER: Incorrectly identifies CFA, SFA, or PFA, but is able to recognize and correct	ER: Incorrectly identifies the superficial compartment but is able to recognize and correct

Table 1: Specific Critical Technical Errors (CTE), Management errors (CME), and Error recovery (ER) for Axillary, Brachial and Femoral Arteries (FA) and Lower Extremity Fasciotomy. CFA = Common, SFA = Superficial and PFA = Profunda. Each error subtracts 2 points and error with recovery one point from the individual procedure score.

	Residents: Before n = 40	Residents: After n=40	Residents: Retent n = 38	Practicing n= 34	Experts n= 10
CTE	112	46	47	55	10
CME	25	55	4	41	1
(CTE + CME+ER)/surgeon	3.8	3.0	1.6	2.8	1.4
ER	16	18	10	12	3
ER/(CTE + CME+ER)	16/153	18/119	10/61	12/108	3/14
% ER	10.4%	15.1%	16.4%	11.1%	21.4%
%ER/surgeon (n)	0.26	0.38	0.4	0.33	2.1

Table 2: Critical Technical (CTE), Management Errors (CME) and Error Recovery (ER) during interval evaluation of Residents before, after, and 12-18 month retention (Reten) following skills training in comparison to practicing and expert surgeons. n = number in each cohort

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